Fermilab FERMILAB-Conf-00/115-E CDF/D0 June 2000

TOP QUARK RESULTS FROM THE TEVATRON COLLIDER EXPERIMENTS

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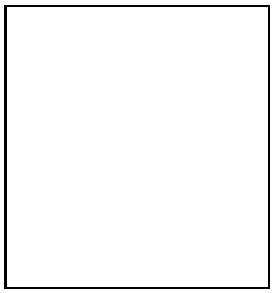

We present the latest results about the top quark obtained at the Fermilab Tevatron Collider by the CDF and DØ experiments. Production cross section and mass measurements are briefly summarized. We report on studies of the top P_T distribution in $t\bar{t}$ production and of the mass of the $t\bar{t}$ system. Properties of the top decay are reviewed: $\Gamma(t \to Wb)/\Gamma(t \to Wq)$, helicity of the W's from top decay and correlations of decay products. Finally, new results on searches for electroweak production of single top are reported.

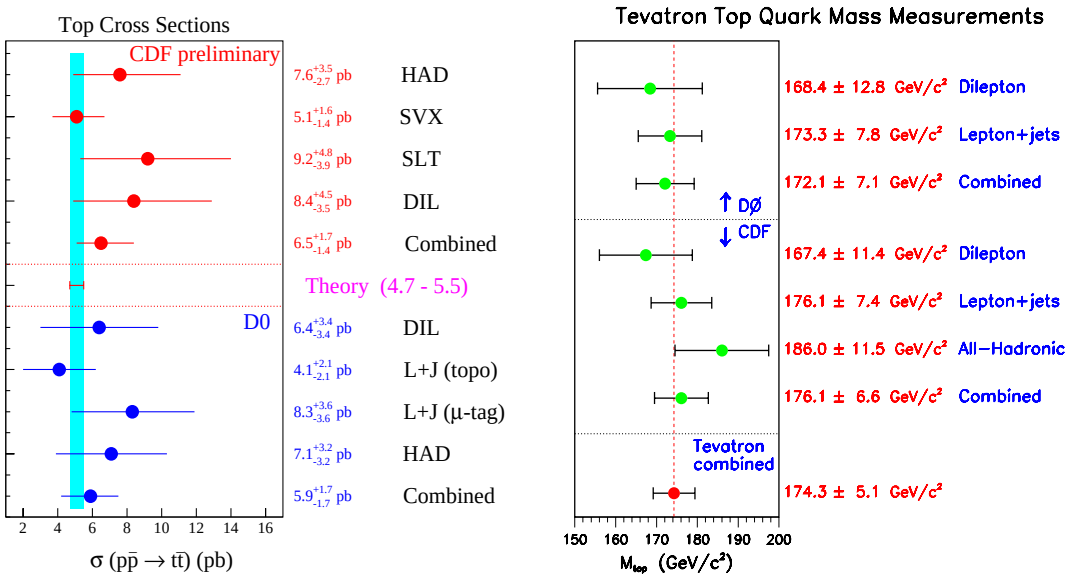

Figure 1: Cross section (left) and mass (right) measurements by CDF and DØ.

1 Introduction

At the Tevatron energy ($\sqrt{s} = 1.8\ TeV$) top quarks are produced primarily via the process $p\bar{p} \to t\bar{t}$. In the Standard Model (SM) each top quark decays almost exclusively into a real W and a b quark ($t \to Wb$). Each W subsequently decays into either a charged lepton and a neutrino or two quarks. The $t\bar{t} \to W^+bW^-\bar{b}$ events can thus be identified by means of different combinations of energetic leptons and jets. The branching ratio for both W's from a $t\bar{t}$ pair to decay leptonically is: 2/81 for $e\mu$, $e\tau$, $\mu\tau$ and 1/81 for ee, $\mu\mu$, $\tau\tau$ (*dilepton channels*). Decay modes of $t\bar{t}$ pairs in which one W boson decays hadronically and the other leptonically (*single-lepton channel*) have a branching ratio of 24/81. When both W's decay hadronically (*all-hadronic channel*) the branching ratio is 36/81. CDF and DØ searched for the top quark using most of these signatures. Candidate events have been detected so far in almost all the expected decay channels.

After the top discovery [1, 2] the Tevatron experiments moved to detailed studies of its properties. In this paper we describe some of the most recent analyses. All the results are based on a data sample corresponding to about 110 pb^{-1}, collected during Run I (from 1992 to 1995).

2 Production Cross Section

By measuring the $t\bar{t}$ production cross section $\sigma_{t\bar{t}}$ in as many channels as possible we can test in principle the SM predictions in great detail.

In Fig. 1 (left) we show the results of the CDF [3] and DØ [4] cross section calculation for each $t\bar{t}$ channel, as well as the combined measurement for each experiment and the value predicted from the theory. CDF updated its cross section measurement during the last year, due to a better understanding of the b-tagging efficiency.

3 Mass Measurements

The top quark mass is a fundamental parameter of the SM. Precise measurements of the top quark and W boson masses constrain the mass of the Higgs boson. Direct top mass measurements were made by CDF [5] and DØ [6] in several channels, and are summarized in Fig. 1 (right). The two collaborations produced also a Tevatron average top mass [7], taking into account the correlations in the systematic

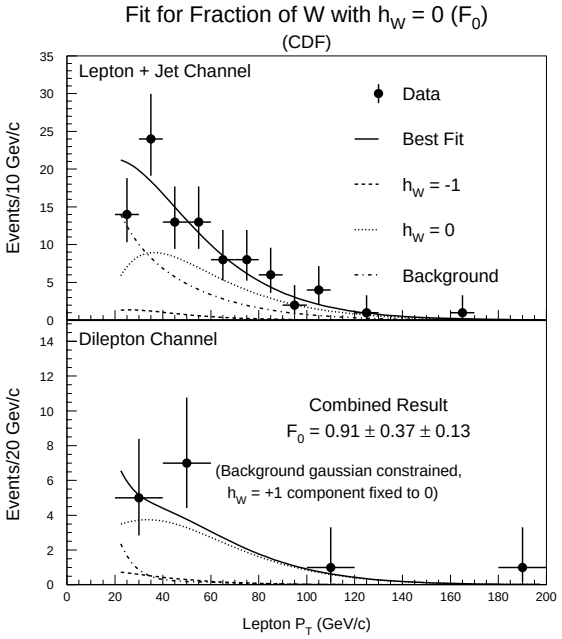

Figure 2: Observed lepton P_T distribution in lepton + jets and dilepton top events, used to extract $\mathcal{F}_{long}$ (CDF).

errors:

$$M^{top}_{Tevatron} = 174.3 \pm 3.2(stat) \pm 4.0(syst) GeV/c^2. \quad (1)$$

4 V_{tb} Measurement

The top quark branching fraction $B = \Gamma(t \to Wb)/\Gamma(t \to Wq)$ is predicted to be almost 1 in the SM. Its measurement allows to extract the CKM matrix element $|V_{tb}|$. Assuming CKM unitarity, $B = |V_{tb}|^2$. A large deviation of B from its SM value would indicate the presence of non–SM effects in the top sector. In this analysis CDF uses the dilepton and the lepton plus four jets samples. Each sample is divided into subsamples according to the presence of identified b tags (0, 1 and 2 tags). B is measured from the ratios of double b–tagged, single b–tagged and un–tagged events. Using the efficiency for tagging a b jet and a Monte Carlo model of the b acceptance in top events, B can be extracted from a likelihood fit. The fit result is $B = 0.94^{+0.31}_{-0.24}(stat + syst)$. Assuming unitarity, this can be converted into a lower limit on $|V_{tb}|$. We find $|V_{tb}| = 0.97^{+0.16}_{-0.12}$ or $|V_{tb}| > 0.78$ (0.75) at 90 (95) % C.L..

5 W Boson Helicity in Top Decay

For a top mass of 175 GeV/c^2 the SM predicts that 70 % of the W bosons from top are longitudinally polarized and 30 % are left–handed. Large deviations from these predictions would indicate that the top quark has non-SM couplings. The relevant information on W boson polarization can be extracted from the decay angular distribution of the charged lepton in the rest frame of the top. However, this requires full reconstruction of the event, with its uncertainties due to combinatorics.

CDF uses the observed lepton P_T spectrum, which also carries this information but does not require event reconstruction [8]. In Fig. 2 we show the charged lepton P_T for single lepton (upper plot) and dilepton (lower plot) candidates. The solid line is the best fit to the data. A maximum likelihood is used to estimate the fraction of W's with helicity=0, assuming that there are no right handed decays. The result is:

$$\mathcal{F}_{long} = 0.91 \pm 0.37\ (stat) \pm 0.13\ (syst).$$

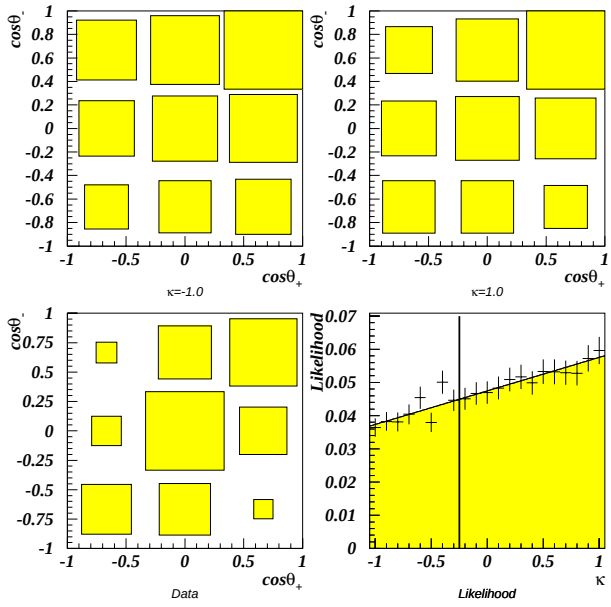

Figure 3: DØ spin correlation study: plots of probability density in the dilepton channel in $(\cos\theta_+, \cos\theta_-)$ phase space.

To evaluate a possible right handed contribution, the longitudinal fraction is fixed to the SM prediction and this gives: $\mathcal{F}_{right} = 0.11 \pm 0.15$ $(stat)$ or $\mathcal{F}_{right} < 0.28$ at 95 % C.L..

With the present statistics no deviation from SM is observed.

6 Top–Antitop Spin Correlations

The spins of the two top quarks are highly correlated in SM $t\bar{t}$ production. The top quark decays so quickly that the angular distribution of the decay products contain information about its initial spin. Leptons and d–type jets are most sensitive to the top spin. For events $t\bar{t} \to \ell^+\ell^- + X$ the correlation between the two leptons can be written as:

$$\frac{1}{\sigma}\frac{d^2\sigma}{d(\cos\theta_+)d(\cos\theta_-)} = \frac{1 + k\cos\theta_+\cos\theta_-}{4}$$

where $\theta_\pm$ is the angle of the lepton momentum with respect to the so called "optimal off diagonal" reference axis [9]. The correlation information is contained in the k factor. SM predicts $k \approx 0.9$. DØ uses top dilepton events (6 candidates) reconstructed as for the dilepton mass analysis to check this correlation [10]. With two neutrinos in the final state the event is kinematically underconstrained, so each event provides a probability distribution for $\theta_\pm$ which is plotted in a 2D histogram for each event. In Fig. 3 the data (lower left) are compared to Monte Carlo templates for $k = 1$ and $k =$ -1 (upper plots). A binned maximum likelihood fit is used to estimate a lower limit on k (lower right): $k >$ -0.25 at 68 % C.L..

7 Invariant mass of the $t\bar{t}$ system

CDF and DØ have looked at the $t\bar{t}$ invariant mass. A peak is expected if the $t\bar{t}$ system comes from the decay of another heavy object. The event selection is similar to that used for the top mass analysis. In Fig. 4 the reconstructed mass is shown for CDF (left) and DØ (right).

CDF evaluates limits on the cross section for production of narrow resonances decaying to $t\bar{t}$ [11]. At 95 % C.L. CDF excludes the existence of a "leptophobic" Z' boson (in a model of top–color assisted technicolor [12]) with mass $M_{Z'} < 480$ GeV/c^2 for natural width $\Gamma = 0.012\ M_{Z'}$ and $M_{Z'} < 780$ GeV/c^2 for $\Gamma = 0.004\ M_{Z'}$.

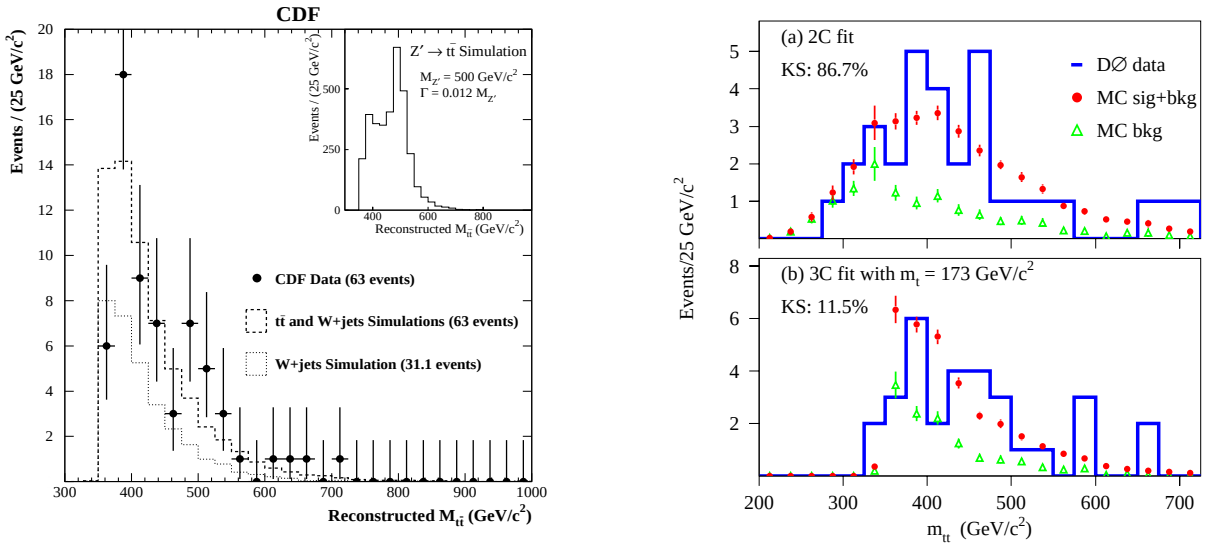

Figure 4: Invariant mass of the $t\bar{t}$ system at CDF (left) and DØ(right).

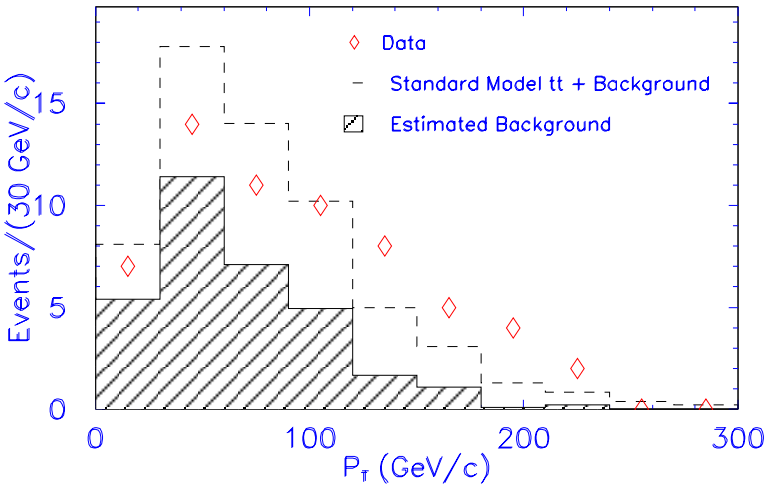

Figure 5: Top P_T distribution for the hadronically decaying top candicates in the lepton + jets sample (CDF).

8 Top P_T distribution

The top P_T spectrum has been investigated in details because it is sensitive to models that predicts anomalous top quark production [13]. The lepton + jets sample is used at CDF for this study [14]. The events are fully reconstructed. The transverse momentum of the hadronically–decaying top candidate is used as a measure of the top quark P_T distribution (see Fig. 5). There is a bias due to reconstruction and resolution effects. To extract the P_T spectrum of produced top quarks we unfold the reconstruction smearing and correct for acceptance as a function of top P_T (in four bins of true top P_T). We perform an unbinned likelihood fit to the measured P_T distribution to extract the fraction of top quarks produced in the 4 P_T bins. The result of the fit is shown in Table 1. The 95 % C.L. upper limit on R_4 (i.e., the fraction of top quarks produced with $225 < P_T < 300$ GeV/c) is: $R_4 < 0.16$.

9 Electroweak single top production

At the Tevatron single top is also expected to be produced through weak interactions. Although the cross section is smaller than that for top pair production, single top production can be used to directly measure in an independent way the CKM matrix element V_{tb}. The two dominant processes at the

Table 1: Fractions of top quarks produced in 4 bins of true top P_T and SM predictions.

P_T bin	Measurement	SM
$0 \leq P_T \leq 75$ GeV	$R_1 = 0.21^{+0.22}_{-0.21}(\text{stat})^{+0.10}_{-0.08}(syst)$	0.41
$75 \leq P_T \leq 150$ GeV	$R_2 = 0.45^{+0.23}_{-0.23}(\text{stat})^{+0.04}_{-0.07}(\text{syst})$	0.43
$150 \leq P_T \leq 225$ GeV	$R_3 = 0.34^{+0.14}_{-0.12}(\text{stat})^{+0.07}_{-0.05}(\text{syst})$	0.13
$225 \leq P_T \leq 300$ GeV	$R_4 = 0.000^{+0.031}_{-0.000}(\text{stat})^{+0.024}_{-0.000}(\text{syst})$	0.025
$0 \leq P_T \leq 150$ GeV	$R_1 + R_2 = 0.66^{+0.17}_{-0.17}(\text{stat})^{+0.07}_{-0.07}(\text{syst})$	0.84

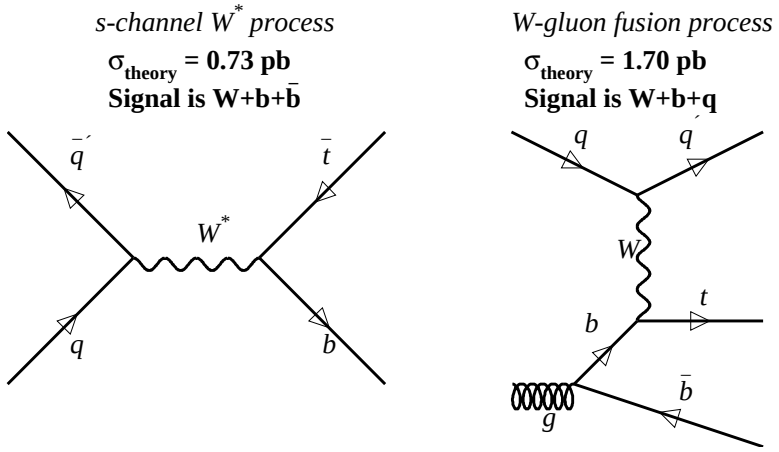

Figure 6: Single top production diagrams.

Tevatron are shown in Fig. 6.

For $W - g$ fusion $\sigma = 1.7 \pm 0.3\ pb$ [15]. The q' jet is expected to be energetic, while the b jet at the lower vertex is soft. The signature in the final state is a W boson plus one b and one light quark jet.

For the W^* channel $\sigma = 0.73 \pm 010\ pb$ [16]. Here the b jet is energetic. The signature thus is a W boson plus 2 b jets.

CDF developed two complementary analyses which are briefly described in the following. The Run I data sample is not enough to measure the presence of single top events. It has been used to set an upper limit on the production cross section.

9.1 H_T analysis

The first analysis selects events with a W candidate and 1, 2 or 3 jets, of which al least 1 is b-tagged. The H_T distribution, defined as the scalar sum of the transverse energies in the event ($H_T = \Sigma E_T\{jets, lepton, \nu\}$) is very similar for both single top production processes. The H_T distribution of data is shown in Fig. 7. An unbinned likelihood fit is used to compare H_T of data to signal plus background and to obtain a 95% C.L. limit on the total single top production cross section:

$$\sigma_{95} < 13.5\ pb.$$

9.2 Individual Cross Section Limits Method

The second analysis selects events with a W candidate and exactly 2 jets, and defines two exclusive $W + 2$ jets samples:

1. Single b–tagged events.
2. Double b–tagged events.

For single b–tagged events we use the $Q \times \eta$ distribution, where Q is the charge of the lepton and η is the pseudorapidity distribution of the untagged jet (shown in Fig. 8 left). In top events from W–gluon

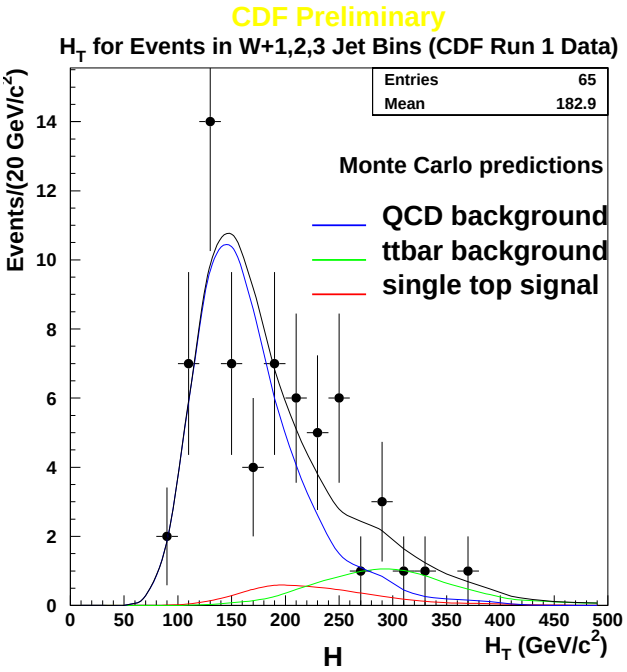

Figure 7: H_T distribution for data and Monte Carlo prediction (CDF).

Table 2: Expected top event yields for each experiment in 2 fb^{-1} of data.

Channel	Yield
Dilepton	150
Lepton + Jets b tag	1000
Lepton + Jets double b tags	300

fusion the charge of the top (hence of the lepton) is correlated with η of the light quark jet. Therefore $Q \times \eta$ is expected to be asymmetric for signal events.

For double b–tagged events we use the reconstructed top mass distribution (shown in Fig. 8 right).

The upper limit on the combined cross section is extracted from a combined likelihood function for single b-tagged and double b-tagged events:

$$\sigma < 18.6\ pb \text{ at } 95\ \%\ \text{C.L.}.$$

10 Run II Prospects

A new data taking period (Run II) will start soon. Both detectors have been improved, concerning tracking and b tagging capabilities. The Tevatron energy will increase from $\sqrt{s} = 1.8$ to $2.0\ TeV$, resulting in a 40% increase in the $t\bar{t}$ cross section. The two experiments are expected to collect 2 fb^{-1} of data in the first 2 years of data taking. Table 2 shows the expected top event yields.

11 Conclusions

CDF and DØ observed in Run I about one hundred top event candidates each. The top quark is now very well measured:

$$\sigma_{CDF} = 6.5\ ^{+1.7}_{-1.4}\ \text{pb}$$
$$\sigma_{D\emptyset} = 5.9 \pm 1.7\ \text{pb}$$
$$\text{M}_{Tevatron} = 174.3 \pm 5.1\ \text{GeV/c}^2.$$

The Tevatron experiments moved already beyond the discovery phase to the detailed study of top properties. Many analyses shown here have not achieved a very high sensitivity because of the small

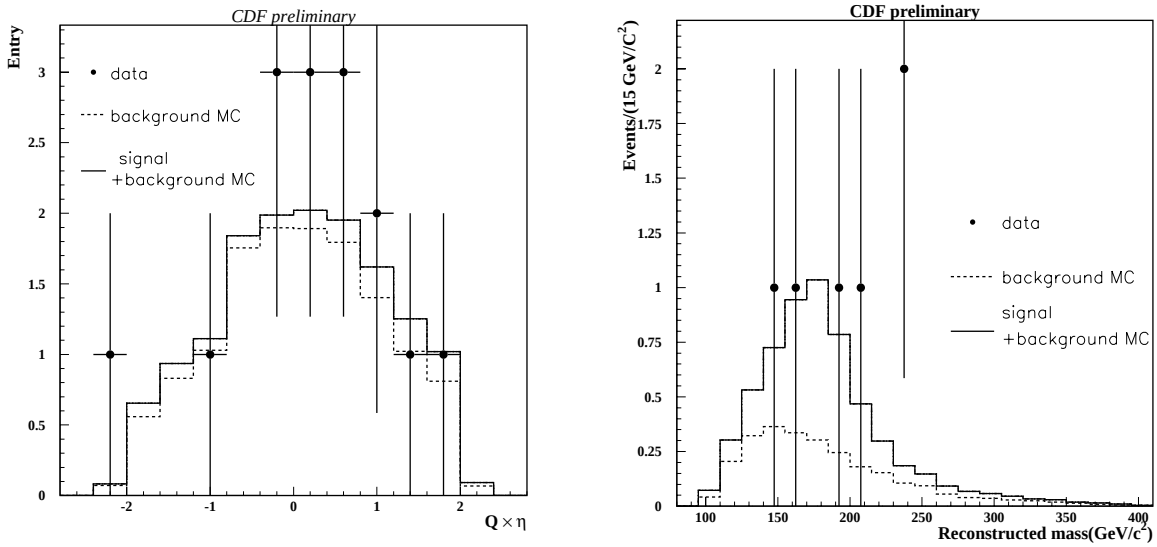

Figure 8: $Q \times \eta$ distribution (left) and reconstructed top mass distribution for double b–tagged W + 2 jet events (right). The points show the data, the solid line shows the fitted signal + background Monte Carlo (CDF).

sample of top quarks. However, they can be viewed as a preview of possibilities in the next Tevatron run. Up to now the top quark looks like a SM object. Top physics will be a rich field of study at the Tevatron in Run II.

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